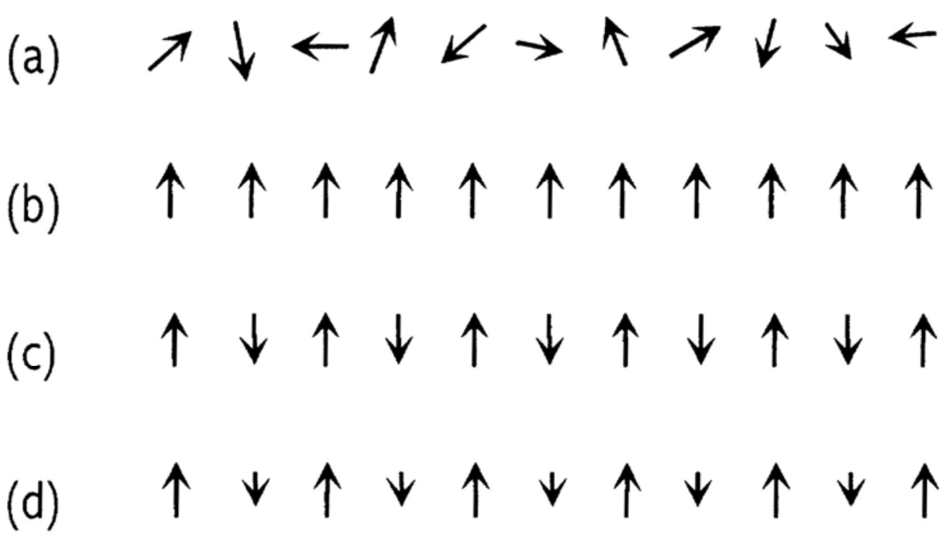
Magnetic Properties of Solids

Magnetic Properties

Materials
- → Magnetic (with unpaired electron)
- → Non-magnetic or diamagnetic (electrons all paired up)



- (a) → Paramagnetic
- (b) → Ferromagnetic
- (c) → Antiferromagnetic
- (d) → Ferrimagnetic

Magnetic Behavior

$$B = \mu H$$

$$B = \mu_0 H + \mu_0 M$$

Induction generated by the field ($\mu_0 H$)

Induction generated by the sample ($\mu_0 M$)

B: magnetic flux density

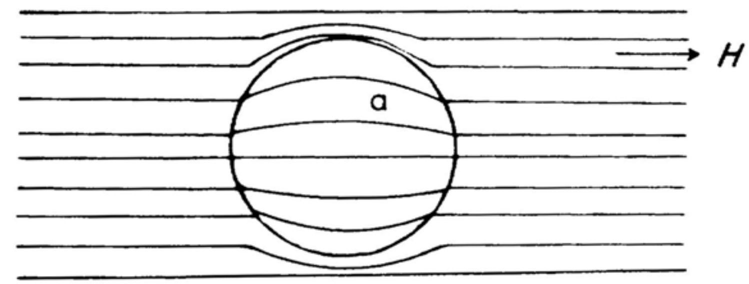
μ: permittivity (m_0: free space)

H: magnetic field

M: Magnetization

$$\chi = M/H$$

χ: magnetic susceptibility



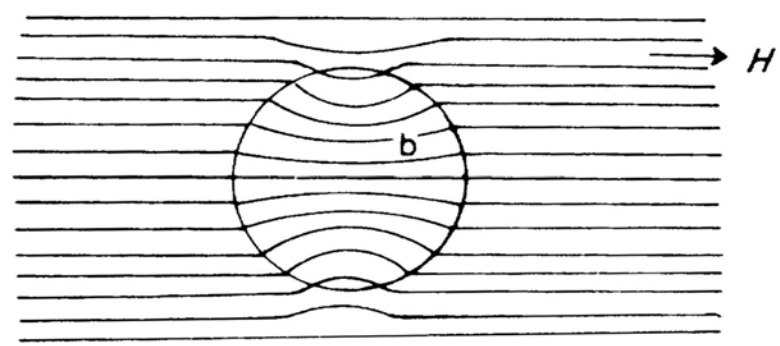
$$B = \mu_0 H + \mu_0 H \chi$$

$$B = \mu_0 H\,(1 + \chi) = \mu H$$

$$\mu_0\,(1 + \chi) = \mu$$

$$(1 + \chi) = \mu / \mu_0 = \mu_r$$

μ_r: relative permittivity



Behavior of Substances in a Magnetic Field

Behaviour	Typical χ value	Change of χ with increasing temperature	Field dependence?
Diamagnetism	-8×10^{-6} for Cu	None	No
Paramagnetism		Decreases	No
Pauli paramagnetism	8.3×10^{-4} for Mn	None	No
Ferromagnetism	5×10^{3} for Fe	Decreases	Yes
Antiferromagnetism	0 to 10^{-2}	Increases	(Yes)

Magnetic behavior may be distinguished by the values of χ and μ and by their *temperature* and *field* dependence

1. *Positive vs. negative value*: only diamagnetic materials show negative χ
2. *Absolute value*: ferromagnetic materials show huge positive value
3. *Temperature dependence*: diamagnetism is not temp. dependence, antiferromagentic materials increase with increasing temp, and para- and ferromagnetic materials decrease with increasing temp
4. *Field dependence*: only ferro- and antiferromagnetic materials show field dependence

Effect of Temperature

Paramagnetic substance: obey Curie Law

$$\chi = \frac{C}{T}$$

C: Curie constant

T: temperature

There is ***no*** spontaneous interaction between adjacent unpaired electrons. *With increasing temperature the alignment is more difficult* and χ decreases.

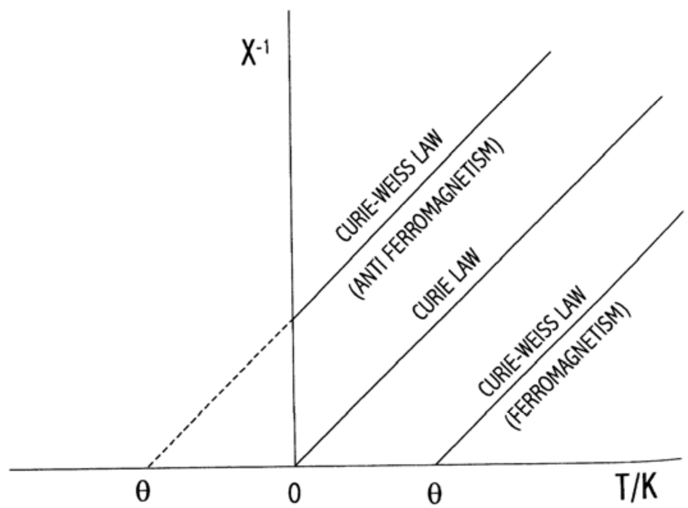
Paramagnetic substance show some magnetic ordering (ferro- or antiferro): Curie-Weiss Law

$$\chi = \frac{C}{T - \theta}$$

θ: Weiss constant

There is ***some*** spontaneous interaction between adjacent spins. A better fit to the high temperature behavior in the paramagnetic region is provided by Curie-Weiss Law (with additional Weiss constant).

Effect of Temperature



Paramagnetic: Curie law; T decrease, c increase (alignment easier)

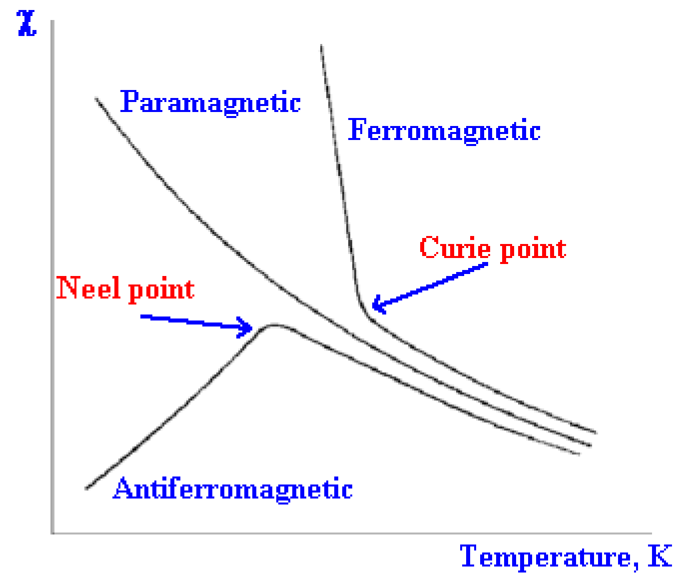


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Table 8.2 *Some Curie and Néel temperatures*

Material	T_c (°C)	T_N (°C)
Cr		35
Mn		−173
Fe	770	
Co	1131	
Ni	358	

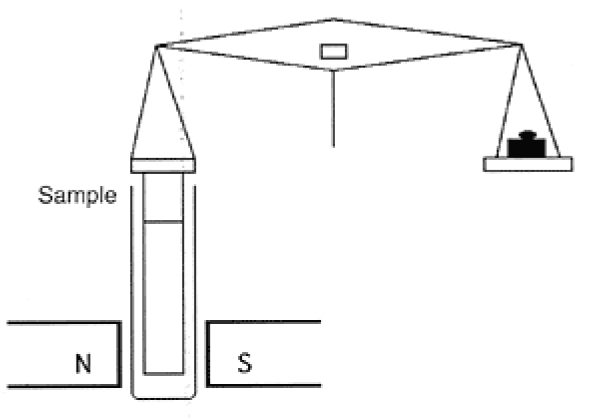
T_c: ferromagnetic Curie temperature (below T_c, sample is ferromagnetic)

T_N: Néel Temperature (below T_N, sample is antiferromagnetic)

Magnetic Moments

Magnetic moment (μ): relates directly to the *number of unpaired electrons*

Susceptibility and magnetic moment can be determined experimentally using a *Guoy Balance:*



For paramagnetic substance, unpaired electrons are attracted by the magnetic field and an apparent increase in mass of the sample occurs when the field is switch on

www.geneq.com

Electron Spin Magnetic Moment

Magnetic properties of unpaired electrons arise from *electron spin* and *electron orbital motion*

Bohr magneton (BM): A natural constant which arises in the treatment of magnetic effects. The magnetic moment is usually expressed as a multiple of the Bohr magneton.

$$BM = \frac{eh}{4\pi mc}$$

e: electron charge

h: Planck's constant

m: electron mass

c: velocity of light

Magnetic moments of single electron

$$\mu_s = g\sqrt{s(s+1)}$$

$$\mu_s = 1.73 \text{ BM}$$

> 1 unpaired electron

$$\mu_s = g\sqrt{S(S+1)}$$

g: gyromagnetic ratio ~2 (for electron spin magnetic moment)

s: spin quantum number

S: sum of spin quantum number

Electron-Orbit Magnetic Moment

The motion of an electron around the nucleus may in some materials, give rise to an *orbital moment*, which contributes to the overall magnetic moment

$$\mu_{S+L} = [4S(S+1) + L(L+1)]^{1/2}$$

L: orbital angular momentum quantum number

Ion	Number of unpaired electrons	$\mu_{S(calc)}$	$\mu_{S+L(calc)}$	$\mu_{(observed)}$
V^{4+}	1	1.73	3.00	~ 1.8
V^{3+}	2	2.83	4.47	~ 2.8
Cr^{3+}	3	3.87	5.20	~ 3.8
Mn^{2+}	5 (high spin)	5.92	5.92	~ 5.9
Fe^{3+}	5 (high spin)	5.92	5.92	~ 5.9
Fe^{2+}	4 (high spin)	4.90	5.48	5.1–5.5
Co^{3+}	4 (high spin)	4.90	5.48	~ 5.4
Co^{2+}	3 (high spin)	3.87	5.20	4.1–5.2
Ni^{2+}	2	2.83	4.47	2.8–4.0
Cu^{2+}	1	1.73	3.00	1.7–2.2

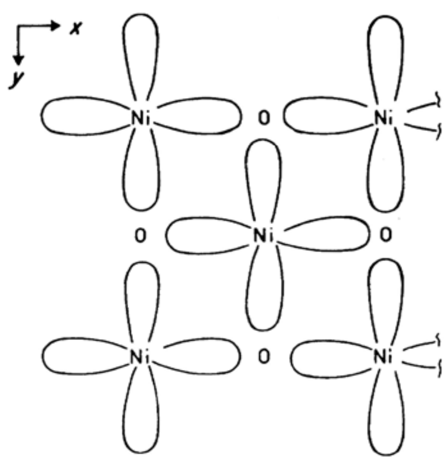
Simplified approach: a single unpaired electron is set equal to 1 BM

$$\mu = gS$$

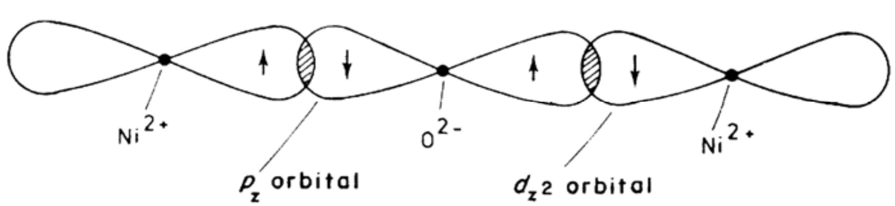
Mechanisms of Magnetic Ordering

The spontaneous alignment of magnetic dipoles in ferro / antiferromagnetic states need some positive energy of interaction between neighboring spins. The origin of this coupling is quantum mechanical.

Antiferromagnetism in NiO: *superexchange*



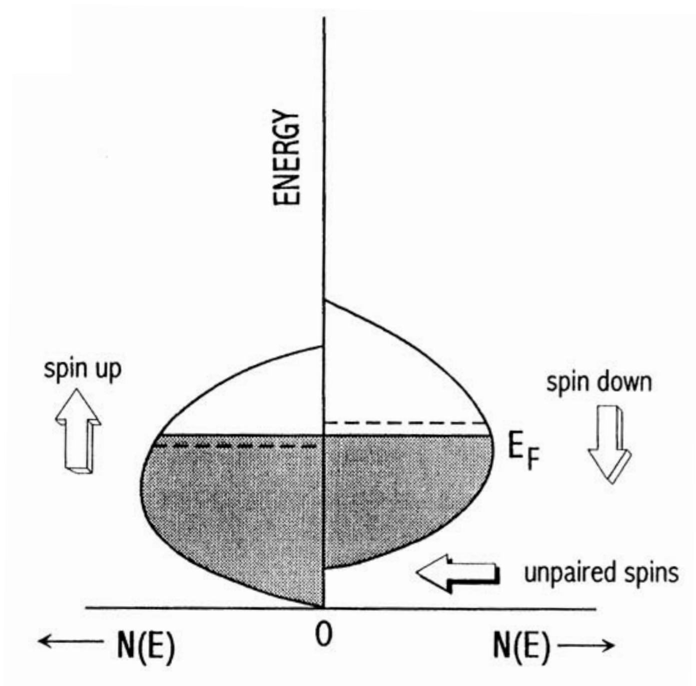
- The unpaired electrons in these e_g orbitals couple with electrons in the p orbitals of the O^{2-} ions.
- p orbitals of the O^{2-} ions contain two electron each, which are coupled antiparallel.



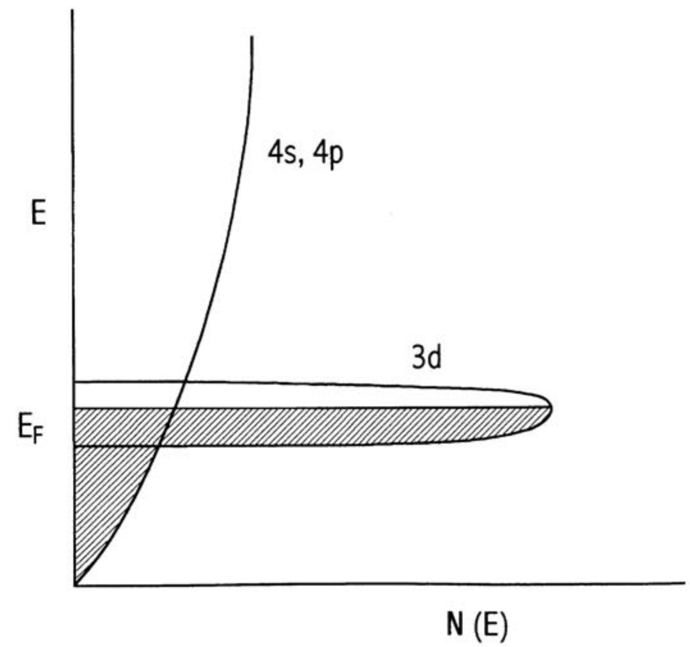
Origin of Para- and Ferromagnetism in Metals

<u>Pauli Paramagnetism</u>

(paramagnetism of *free electrons*)



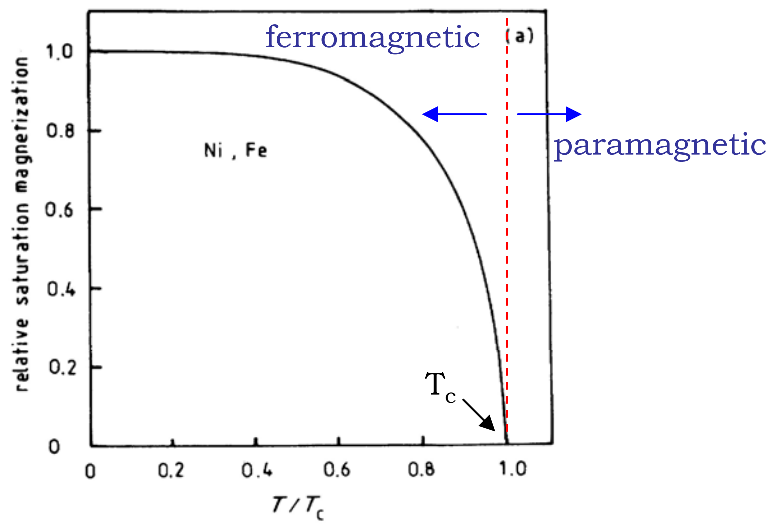
<u>Ferromagnetism</u>



Magnetic Materials-Metal and Alloys

Five transition metals: Cr, Mn, Fe, Co, Ni; and most lanthanides are either ferro- or antiferromagnetic

Fe, Co, Ni are ferromagnetic; Cr and Mn are antiferromagnetic



Perfect magnetic order is attainable only at absolute zero

How many unpaired electrons are available to contribute to ferromagnetism:

Table 8.4 *Electronic constitution of iron, cobalt and nickel*

Metal	Free ion configuration	Ferromagnetic state: Number of unpaired spins	Ferromagnetic state: Configuration
Fe	d^6s^2	2.2	$d^{7.4}s^{0.6}$
Co	d^7s^2	1.7	
Ni	d^8s^2	0.6	

Fact: *2.4 unpaired electron per atom*

(in $Fe_{0.8}Co_{0.2}$ alloy)

Lanthanide Elements

- f-block elements
- f-block unpaired electrons
- They can form both ferro- and antiferromagnetic below room temperature
- Strongest permanent magnet: $SmCo_5$ and $Nd_2Fe_{14}B$

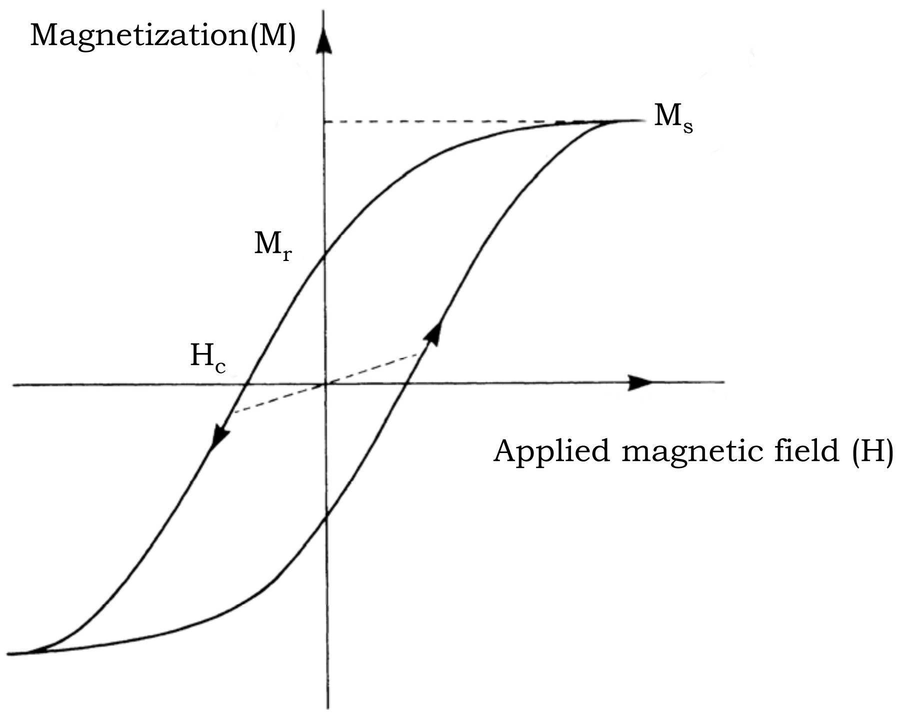
Table 8.5 *Néel (antiferromagnetic) and Curie (ferromagnetic) temperatures (K) in lanthanides.* (Data taken from Taylor, 1970)

Element	Néel temperature T_N	Curie temperature T_C
Ce	12.5	
Pr	25	
Nd	19	
Sm	14.8	
Eu	90	
Gd	—	293
Tb	229	222
Dy	179	85
Ho	131	20
Er	84	20
Tm	56	25

Ferromagnetism

Ferromagnetic materials have *domain structure*

<u>Hysteresis Loop</u>



M_s: Saturation magnetization
M_r : Remanent magnetization
H_c: Coercive magnetic field

Magnetically *Hard*

- High M_r and H_c
- Magnetization remains after the field switch off (permanent magnet)

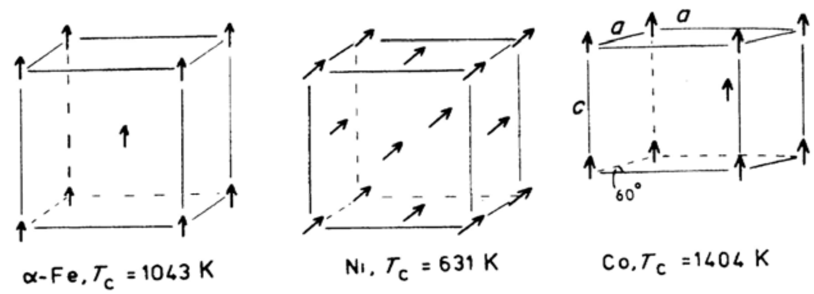
Magnetically *Soft*

- Low M_r and H_c (small area)
- Easily demagnetized

Some More Definitions

1. Magnetocrystalline anisotropy

The energy required to rotate the magnetization out of the preferred direction



2. Eddy current

The source of energy loss in an alternating magnetic field

Energy loss:

$$IV = V^2 / R$$

Eddy currents are minimized in highly resistive materials.

Metal oxides vs. metals

3. Magnetostriction

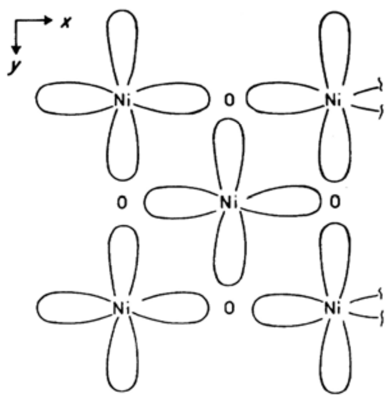
Magnetic materials *change their shape* on magnetization

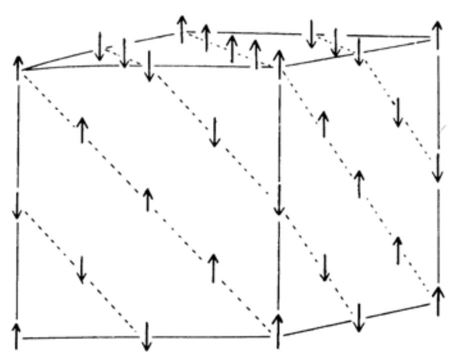
- The effect increase with H
- Dimensional changes involved are small, which is comparable to changing the temperature of the material by a few degree

Transition Metal Oxides

<u>Monoxides</u>

e.g. NiO





<u>Dioxides</u>

TiO_2 ⟶ Diamagnetic or pauli paramagnetic

CrO_2 ⟶ ferromagnetic

MnO_2 ⟶ paramagnetic

- d-band (narrow or broad)
- Localized unpaired electrons
- Coupling between d- and sp orbitals

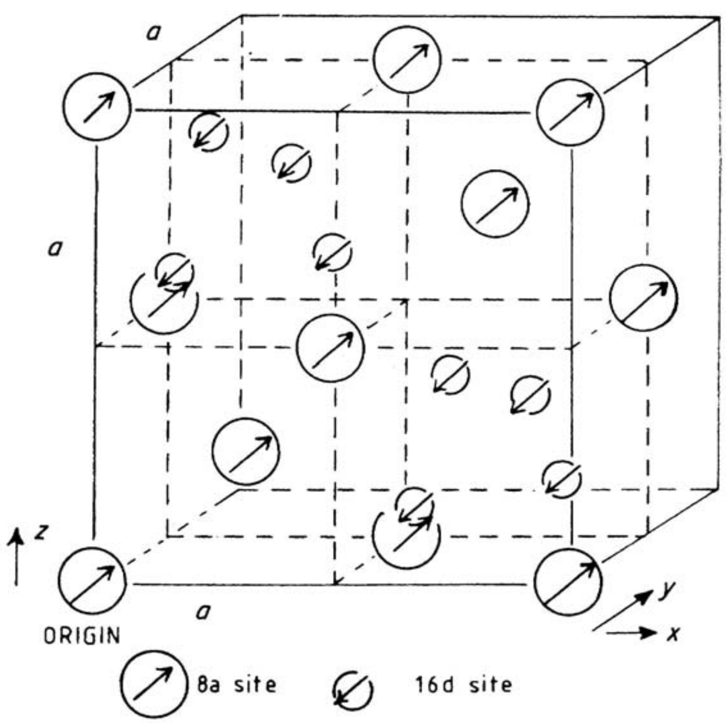
Spinels

Commercially important Ferrites: MFe_2O_4

M = divalent ion, e.g. Fe^{2+}, Ni^{2+}, Mg^{2+}, Zn^{2+}

•Spinel structure: $[Fe^{3+}][M^{2+}, Fe^{3+}]O_4$

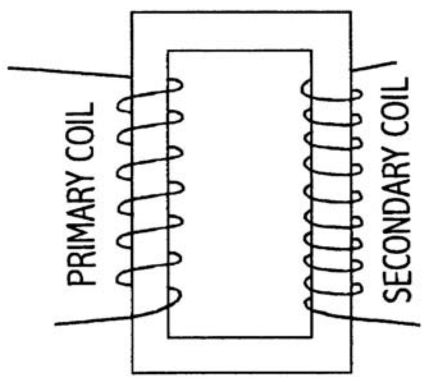
•Antiferromagnetic or ferrimagnetic



Applications

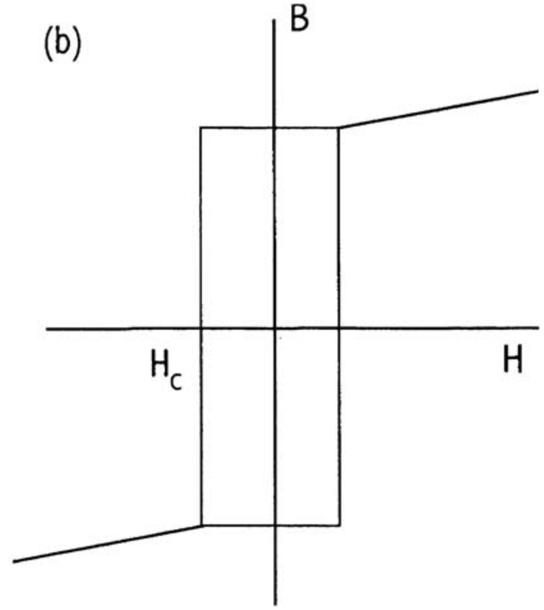
1. Transformers/motor core

- Soft magnetic materials
- Low hysteresis and eddy current loss



2. Information storage

- Soft magnetic materials
- unique hysteresis loop
- binary digital system



3. Permanent magnet

- Hard magnetic materials
- High curie temperature